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Characterizing spectral–temporal patterns of defoliator and bark beetle disturbances using Landsat time series

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ABSTRACT

Defoliators and bark beetles are natural disturbance agents in many forest ecosystems around the world. Mapping the spatial and temporal patterns of insect disturbance dynamics can help in understanding their impacts on forest ecosystem resilience and functioning, and in developing adaptive management strategies. In recent years, much progress has been made in landscape-level analyses of insect-induced disturbances using remotely sensed data. However, many studies have focused on single insect agents or aggregated different insect agents into a single group. In this study, we characterized the temporal-spectral patterns associated with bark beetle and defoliator disturbances using Landsat time series between 1990 and 2013, with the objective to test if the two insect disturbances can be separated with Landsat data. We analyzed a recent outbreak of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and western spruce budworm (*Choristoneura freemani* Razowski) in British Columbia, Canada. To characterize the disturbance and recovery trends associated with insect disturbances we used the LandTrendr segmentation algorithm. We fitted LandTrendr spectral trajectories to annual normalized burn ratio (NBR) and Tasseled Cap (TC) time series, from which we then extracted a set of disturbance metrics. With these disturbance metrics, two random forest models were trained to a) distinguish insect disturbances from harvest and fire disturbances; and to b) attribute the insect disturbances to the most likely agent, i.e. mountain pine beetle or western spruce budworm. Insect disturbances were successfully mapped with an overall accuracy of 76.8%, and agents were successfully attributed with overall accuracies ranging from 75.3% to 88.0%, depending on whether only pure host-stands or mixed stands with both insect hosts were considered. In the case of mixed host stands, nearly 45% of the western spruce budworm disturbances were falsely attributed to mountain pine beetle. Spectral metrics describing disturbance magnitude were more important for distinguishing the two insect agents than the disturbance duration. Spectral changes associated with western spruce budworm disturbances had generally lower magnitudes than mountain pine beetle disturbances. Moreover, disturbances by western spruce budworm were more strongly associated with changes in TC greenness, whereas disturbances by mountain pine beetle were more strongly associated with changes in TC brightness and wetness. The results reflect the ephemeral nature of defoliators versus the tree mortality impacts of bark beetles in our study area. This study demonstrates the potential of Landsat time series for mapping bark beetle and defoliator disturbances at the agent level and highlights the need for distinguishing between the two insect agents to adequately capture their impacts on ecosystem processes.

1. Introduction

Insect disturbances play an important role in forest ecosystem dynamics by renewing old and susceptible forests, recycling nutrients, and providing food for wildlife (Parker, Clancy, & Mathiasen, 2006). There is increasing evidence that human actions through management and climate change have altered the interactions between insects and forests, resulting in more widespread insect outbreaks (Raffa et al., 2008; Schoennagel, Veblen, & Romme, 2004; Swetnam & Lynch, 1993). Using climate change projections, current research indicates that outbreaks will become more frequent in the future (Logan, Régnière, & Powell, 2003; Volney & Fleming, 2000; Woods, Heppner, Kope, Burleigh, & Maclauchlan, 2010), which will have significant consequences for the future carbon balance of forests (Hicke et al., 2012; Kurz et al., 2008a; Kurz, Stinson, Rampley, Dymond, & Neilson, 2008b).

Monitoring insect outbreaks with remote sensing data systematically over space and time can help with understanding landscape-scale causes and consequences of insect disturbances. Two of the most prevalent insect agents causing widespread tree damage and mortality are bark beetles and defoliators. Since impacts of defoliators and bark beetles on ecosystem function and structure are different (Hicke et al., 2012),

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distinguishing between insect agents is important to adapt forest management strategies and to improve ecosystem process models. However, studies mapping insect disturbances over large areas usually group defoliators and bark beetles into a single disturbance category (Huang et al., 2010; Kennedy et al., 2012; Masek et al., 2013).

In coniferous forests of North America, the most important bark beetle is the mountain pine beetle (*Dendroctonus ponderosae* Hopkins). Mountain pine beetles reproduce in the phloem below the bark and introduce a fungus, which clogs the phloem and limits the translocation of water and nutrients through the tree. By using pheromones, the beetles usually follow a cooperative behavior strategy (mass attack) to help overcome the defensive system of trees. Attacks by mountain pine beetle are not noticeable in the first year of infestation (green-attack stage) but typically lead to complete discoloration (red-attack stage) in the second year and complete defoliation (gray-attack stage) in the third year (Wulder, Dymond, White, Leckie, & Carroll, 2006a). However, the progression of infestation by mountain pine beetle can vary by region, site, and species (Wulder et al., 2006a).

In comparison to bark beetles, defoliating insects cause mild to moderate disturbances (Cooke, Nealis, & Regniere, 2007). The most prominent defoliators in coniferous forests of North America are in the genus *Choristoneura* (spruce budworm), including the eastern spruce budworm (*Choristoneura fumiferana* Clemems), the jack pine budworm (*Choristoneura pinus pinus* Freeman), the western spruce budworm (*Choristoneura freemani* Razowski), the 2-year-cycle spruce budworm (*Choristoneura biennis* Free.), and the coastal spruce budworm (*Choristoneura orae* Free.) (Nealis, 2008). From those, the western spruce budworm is most important for western North America (Hicke et al., 2012). Western spruce budworm larvae feed primarily on current-year foliage, which can lead to chlorosis, crown dieback, and tree death; particularly when insect populations are high over several years and in cases of secondary infestation by bark beetles (Alfaro, Thomson, & Van Sickle, 1984; Alfaro, Van Sickle, Thomson, & Wegwitz, 1982; Shepherd, 1994). Nonetheless, if defoliation rates are low, most trees typically will experience little damage and recover within several years (Campbell, Smith, & Arsenault, 2006; Shepherd, 1994). Western spruce budworm outbreaks return every 30 years on average, though the intensity of outbreaks can vary significantly (Alfaro, Berg, & Axelson, 2014; Axelson, Smith, Daniels, & Alfaro, 2015).

Previous studies have shown that Landsat's spectral bands can be used to discriminate healthy forests from insect disturbed forests. Also, with a 30 m spatial resolution, Landsat operates at a scale that is informative for ecological research and management decisions (Cohen & Goward, 2004; Wulder et al., 2008). Early studies utilizing Landsat for insect disturbance mapping in coniferous forests typically used spectral information from one or two images, including the Tasseled Cap components (Franklin, Waring, McGreight, Cohen, & Fiorella, 1995; Skakun, Wulder, & Franklin, 2003), spectral bands (Franklin, Wulder, Skakun, & Carroll, 2003), spectral mixture analysis (Radeloff, Mladenoff, & Boyce, 1999), and vegetation indices based on near-infrared and shortwave-infrared reflectance (Franklin, Fan, & Guo, 2008). However, approaches based on single years and binary maps are somewhat restricted in characterizing the complex ecological dynamics of insect outbreaks. Thus, a more comprehensive mapping approach is needed, utilizing as many points in time as possible and characterizing the disturbance magnitude and duration (Gillanders, Coops, Wulder, Gergel, & Nelson, 2008; Kennedy et al., 2014).

Following the opening of the United States Geological Survey (USGS) Landsat archive and the related increase in capacity to produce time series (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012), annual Landsat time series were successfully used in a number of studies to capture insect-infestation. While implemented just prior to the opening of the USGS archive, Goodwin et al. (2008) used annual Landsat time series to capture infestation by mountain pine beetle in British Columbia. In this study, spectral trajectories displayed little to no change in the first year of infestation, but a decreasing trend in subsequent years. Similar spectral and temporal trends were found for mountain pine beetle in Montana (Assal, Sibold, & Reich, 2014), in Colorado (Meddens & Hicke, 2014), and in Oregon (Meigs, Kennedy, & Cohen, 2011). The changes in Landsat spectral trajectories were linked to tree mortality (Meigs et al., 2011; Pflugmacher, Cohen, & Kennedy, 2012), which enabled a landscape-scale assessment of mountain pine beetle impacts (Bright, Hudak, Kennedy, & Meddens, 2014; Meigs, Kennedy, Gray, & Gregory, 2015). Defoliator disturbances were also associated with gradual changes in the spectral signal (Meigs et al., 2011; Vogelmann, Tolk, & Zhu, 2009; Vogelmann, Xian, Homer, & Tolk, 2012), but spectral trajectories were highly variable. Changes during defoliation were explained by decreasing vigor, top-kill, and increasing mortality resulting from consecutive defoliation events, though many trajectories also showed quick spectral recovery after disturbance. Thus, recent studies suggest that Landsat time series can be utilized to characterize the complex spatial and temporal dynamics of insect outbreaks, but spectral trajectories vary considerable among insect agents, regions, and outbreak intensities. To better understand the ecological dynamics of insect disturbances, a better understanding of the spectral–temporal trajectories of individual insect agents is needed, enabling a more detailed mapping of insect disturbances – i.e. by distinguishing between bark beetle and defoliator disturbances.

Here, our goal was to determine the capacity of spectral–temporal trajectories from annual Landsat time series to map defoliator and bark beetle disturbance dynamics in southern-interior British Columbia, Canada. Our specific objectives were to:

1. Test how well bark beetle and defoliator disturbances can be distinguished with Landsat time series.
2. Characterize the spectral–temporal trajectories of bark beetle and defoliator disturbances with respect to severity, duration, and spectral recovery.
3. Map the spatial and temporal pattern of mountain pine beetle and western spruce budworm disturbances.

2. Study site

Our study site is located in the interior of British Columbia, Canada, occupying an area of approximately 149,700 km^2. The outer extent of the study site (hereafter referred to as *Interior*) is delineated by eight Landsat footprints (WRS-2 path/row: 45/25, 45/26, 46/24, 46/25, 46/26, 47/24, 47/25, 48/24; Fig. 1). In British Columbia, a province-wide biogeoclimatic classification system has been established that describes the natural ecozones based on climatic and vegetation characteristics (Pojar, Klinka, & Meidinger, 1987). The Interior is dominated by the Interior Douglas-fir Forest zone (Hope et al., 1991). The Interior Douglas-fir Forest zone is characterized by mature Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands at mid-elevations (900–1200 m), mixed stands of Douglas-fir and ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) at lower elevations (600-900 m), and mixed stands of Douglas-fir and lodgepole pine (*Pinus contorta* Douglas) at higher elevations (1200–1450). The Interior Douglas-fir Forest borders the Montane Spruce zone at higher elevations, which is actually a transition zone to the Engelmann Spruce and Subalpine Fir zone. In the Interior, the Montane Spruce zone is characterized by extensive seral stands of lodgepole pine. At lower elevations, the Interior Douglas-fir Forest borders the Ponderosa Pine zone, which is dominated by open stands of ponderosa pine. In the northern part of the study site, the Interior Douglas-fir Forest borders the Sub-Boreal Pine and Spruce zone. The Sub-Boreal Pine and Spruce zone is dominated by lodgepole pine. The very low elevation areas are part of the largely non-treed bunchgrass zone.

The Interior and in particular the Interior Douglas-fir Forest have experienced a complex history of fire and insect disturbances (Campbell et al., 2006; Maclauchlan, Brooks, & Hodge, 2006). There are records of western spruce budworm outbreaks over the past 400 years,